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Disaggregated analysis of US energy consumption in the 1990s: evidence of the effects of the internet and rapid economic growth

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Abstract

This paper decomposes US energy use from 1988 to 1998 and attributes the changes in energy use to three underlying factors: activity, structure, and intensity. For this study we use a bottom-up methodology, by separately decomposing delivered energy use in six sectors: travel, freight, manufacturing industries, non-manufacturing industries, residential, and services. The most commonly used indicator of energy efficiency in the total economy, the ratio of energy consumed to unit of GDP (E/GDP) created can often be misleading. The rapid decline in the E/GDP ratio in recent years has been used to support assertions that the internet and information technologies in general have enabled improvements in energy efficiencies. However, our disaggregate analysis suggests that energy intensities on average are falling more slowly than ever before while actual energy use increased faster than at any time since 1970. The decline in the E/GDP ratio in the mid- to late 1990s owes much more to structural changes in the demand for energy services than to falling energy intensities. © 2001 Published by Elsevier Science Ltd.

Keywords: Decomposition analysis; Structural change; Internet

1. Introduction

There is no question that the relationship between energy use and economic activity in the US has undergone many transformations since the first oil crisis. In a recent study for the Department of Energy, we examined US energy use during the period from 1970 to 1994 (Murtishaw and Schipper, 2001). Using index decomposition it was demonstrated that reductions in energy-use intensities reduced overall delivered energy use by some 1.7%/yr between 1973 and 1985. Following the drop in oil prices in the mid-1980s, however, intensities began to fall more slowly, particularly for light-duty household vehicles, buildings in the services sector, and manufacturing industries.

This study extends our decomposition analysis of total annual US energy consumption to 1998 using recently released data for the manufacturing and services sectors. We focus on changes in delivered energy use during the 10-yr period from 1988 to 1998, which provides an interesting case study of energy use in the US economy. Between 1988 and 1992 the US economy experienced a recession with real GDP growth averaging only 1.2%. In contrast, between 1992 and 1998 GDP increased 3.6%/yr, driven largely by explosive growth in information technology (IT) related industries.

Much has already been written about the implications of the "new" information economy and its impact on energy and materials use (Romm et al., 1999 and references therein). Some reports have focused on the marked fall in recent years of the ratio of energy use to GDP (E/GDP), a common indicator of economy-wide efficiency. Our study uncovers the underlying trends that affect E/GDP and presents a disaggregated analysis by sector. The approach we employ is a decomposition method that isolates the impacts of changes in activity levels, structural aspects of the economy, and energy intensities on energy use within each sector of the

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economy. We also demonstrate that reliance on the E/GDP ratio alone does not accurately measure how energy–economy relationships in the US economy are changing. This report seeks to clarify the recent debate on efficiency trends in the US and demonstrates the importance of disaggregated analysis in the study of changes in total national energy consumption. To our knowledge there is no other comprehensive disaggregated analysis of US energy uses in recent years as yet available.

If the information economy were having a significant impact on energy use in the US economy, certain energy end uses would be expected to rise or fall relative to the others. For example, freight activity, particularly for non-bulk items sent by trucks or air, may increase as more consumer products are ordered over the web and as more internet-based supply management enables a greater use of just-in-time delivery. A second probable effect is that electronics manufacturing, which generates a relatively large amount of value added per unit of energy use, would account for a greater share of value added in manufacturing and thus lower the aggregate intensity of the manufacturing sector. Finally, the use of IT in business could increase productivity of all factors, by facilitating communication and coordination of activities and enabling some business to exist in largely virtual space, thus requiring less physical space to store or display products. These latter productivity effects are difficult to capture without a disaggregated level of analysis beyond the scope of this report. While this report will attempt to address an analysis of the first two factors, the discussion involving enhanced productivity will by necessity be limited to energy use trends that can only suggest whether the internet economy, and IT more generally, are having such an effect.

We provide an overview of the changes in total and sectoral energy use that occurred between 1988 and 1998 in Section 2. Detailed analyses of energy use by sector and decomposition of changes in energy use into structural and intensity effects are presented in Section 3. Sector-specific data and methodological issues are also provided at the beginning of each corresponding subsection. For space considerations, we omit discussion of the non-manufacturing industries sector (agriculture, mining, and construction), which only consumed about 6% of 1998 total final energy (see Murtishaw et al., 2000, for a study of the non-manufacturing industries). Section 4 returns to a review of energy use across the entire economy, this time decomposed to isolate true energy savings due to declines in energy intensities from changes in energy use driven by structural changes. Finally we summarize our findings in Section 5 and provide concluding thoughts on how IT may or may not be contributing to energy savings in the US economy. We refer readers to Murtishaw and Schipper (2001) for detailed descriptions of the methodologies employed in constructing our indicators and decomposing the trends in the time series. In addition, that report provides a comprehensive list of the principal data sources used for the energy consumption and structural indicators.

The approach used is not new. Schipper et al. (1990) carried out a similar analysis of the US through the late 1980s. Schipper et al. (1993) applied the techniques first to Denmark, then to Sweden. Schipper et al. (2001) applied the AWD indices to energy use in Australia. The Office of Energy Efficiency Office of Natural Resources Canada (OEE, 2000) applies similar techniques each year to measuring changes in energy use in Canada. Earlier efforts (Golove and Schipper, 1997; Schipper et al., 1997b) extended the economy-wide analyses to carbon emissions first to the US and then for a number of IEA member countries.

2. The big picture: total energy use in the US economy

Fig. 1 depicts the trend in the E/GDP indicator from 1988 to 1998, disaggregated by 11 major subsectors. The chart shows that this indicator has continued to decline, from over 9 megajoules (MJ)/\$ to about 8 MJ/\$, a total drop of 14%. However, the average annual rate of decline fell from 2.2% during the period from 1970 to 1988 to 1.5% from 1988 to 1998. The change in energy use was not consistent among all of the sectors. The final two bars in Fig. 1 depict the shares of energy use accounted for by each of the 11 end uses. It is clear from these two bars that the shares of residential space heating, heavy manufacturing, and services fuel consumption fell significantly during this period. In contrast, energy consumption by freight trucks, light manufacturing, other residential end uses, and other travel modes (principally air travel) gained shares of total delivered energy use. The top line in Fig. 1 represents the total use of primary energy per GDP.[1] This indicator fell from 12.6 to 11.5 MJ/\$, a roughly 10% drop in primary intensity. This is somewhat less than the decline in delivered energy per GDP because both the share of electricity in the fuel mix grew and there was a slight increase in the primary coefficient.[2]

These trends in both delivered and primary energy consumption per GDP would seem to indicate some success in energy efficiency improvements in the US

[1] Note that the figure for primary energy used for this indicator is based on a bottom up calculation of our six energy-using sectors and not the official totals from the Energy Information Administration. Our figure is generally about 10% lower that EIA's total primary since our bottom up calculation does not include energy sources used as feedstocks, oil refineries' own consumption, and some miscellaneous energy uses (military, natural gas pipelines, etc.)

[2] The primary coefficient is the amount of primary energy consumed by utilities for every unit of electricity (or heat) delivered to the end user. We determine this coefficient using energy balances from the International Energy Agency.

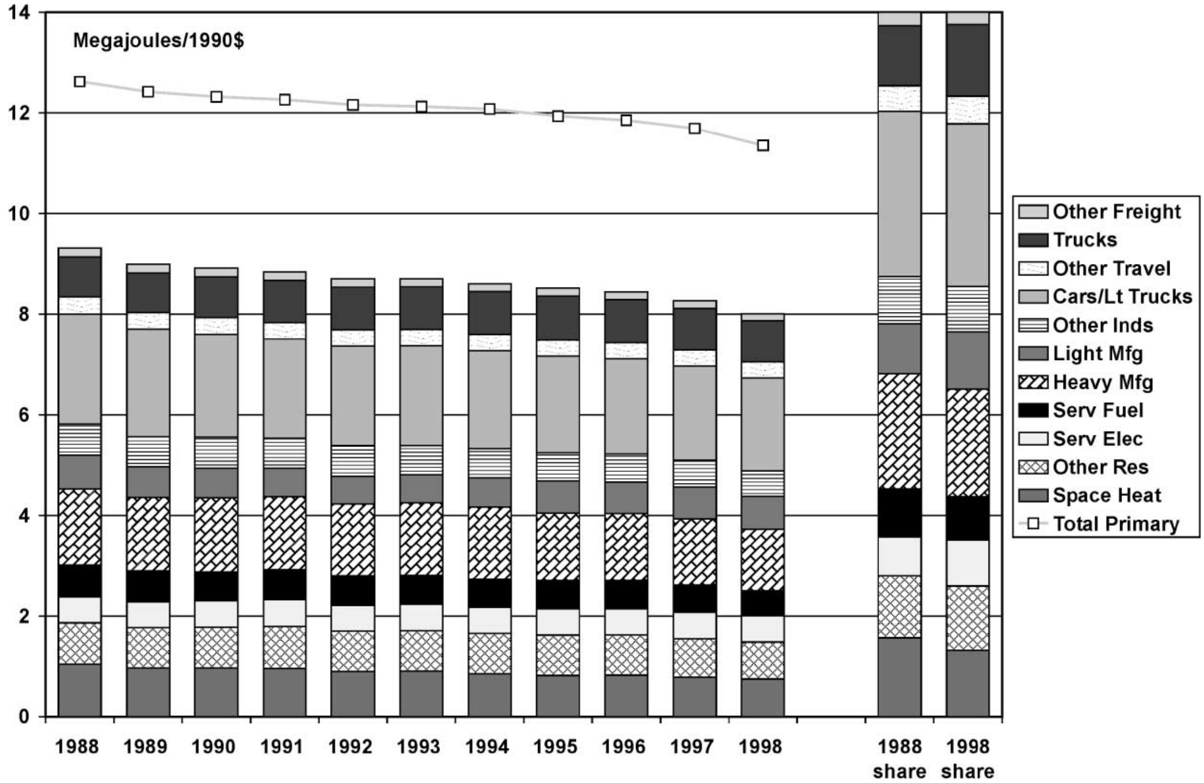

Fig. 1. Delivered energy consumed per GDP by sector, with total primary energy per GDP.

economy during this time span, and indeed the efficiency of many end uses and processes did improve. However, this aggregate E/GDP indicator conflates decreases in energy use due to changes in energy intensities with those due to structural changes in the economy. The following section examines five energy-using sectors in more detail and contrasts the changes in energy use due to structural changes with those due to real declines in energy intensities.

As noted elsewhere (Schipper, 1997; Schipper et al., 1997a), E/GDP is a purely descriptive indicator with no particular normative or analytical meaning related to the efficiency of energy use. To understand why it is changing, one must break down the changes into these components:

changes due to shifts in the mix of activities or outputs from sector to sector, and the mix within each sector, which we label "energy services" and treat explicitly in this paper;

changes due to evolution of individual energy intensities (energy/output or energy/activity), for which we have analyzed roughly 30 in the US economy as far back as 1960;

changes related to the conversion of primary energy into fuels and power and to miscellaneous end-uses (such as military or private aviation, which we do not treat in this paper).

The present study will focus on the first two components of change, since the former is related to structural changes (which may be driven in par by the "new economy") while the latter is more closely related to technological changes called "energy efficiency. " We will show that through the early 1990s, changes from the second of these factors dominated overall changes in US energy use, but from 1994, changes in the structure of output and activities accounted for far more of the drop in the E/GDP ratio than did changes in intensities.

3. Sectoral decompositions of energy use

3.1. Travel

The travel sector consumed about 27% of the total delivered energy in the United States in 1998, a share that has been quite steady over the course of the study period. From 1988 to 1998, travel energy use increased 15%, driven largely by the fact that total pkm rose from 5.4 to 6.6 trillion, as shown in Fig. 2.

Fig. 2 also illustrates how the structure of transportation has changed in the past several years. The last two bars on the right side of the figure show more clearly how the shares have changed relative to each other (see Box 1). The structure of energy uses, defined as the

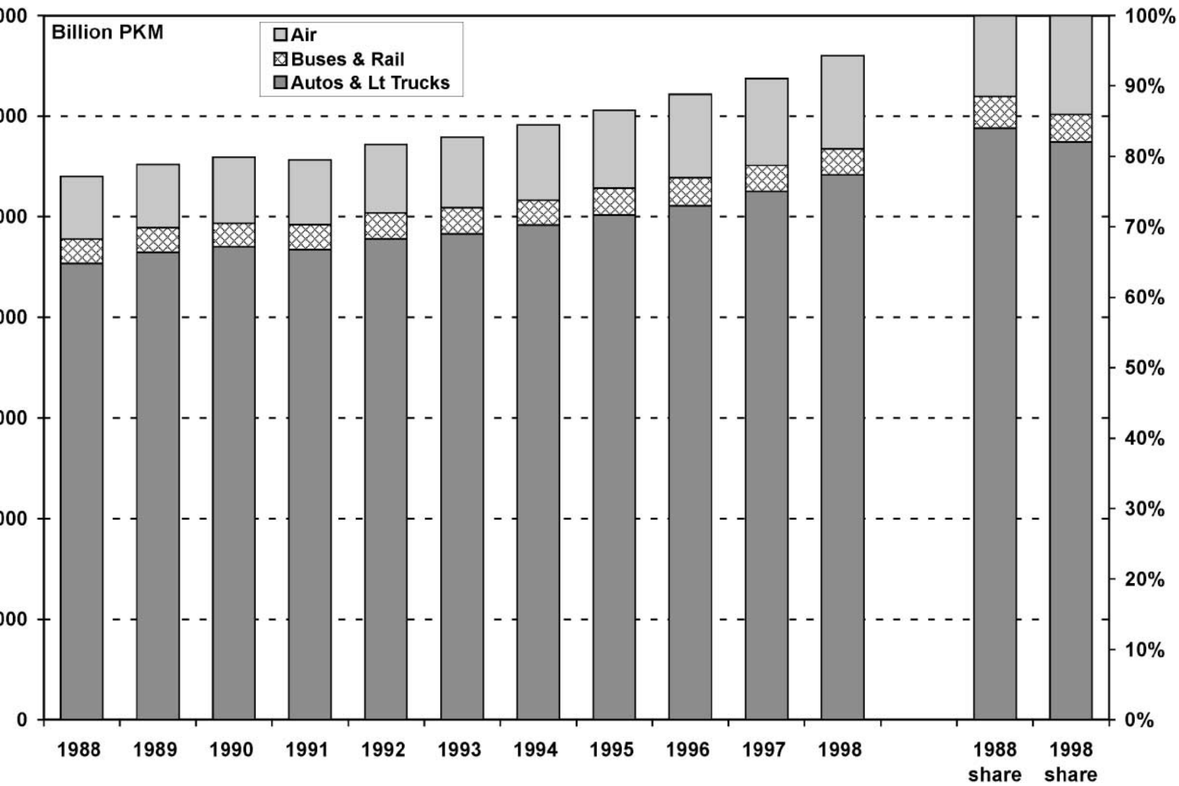

Fig. 2. Travel activity by mode, with 1988 and 1998 shares.

shares of pkm carried by each mode, is clearly dominated by autos and light trucks. While the number of pkm carried by these personal modes grew rapidly, their share of the total fell from 84% to 82% due to the continuing rapid rise in air travel. However, the rate of growth in air travel has slowed to about 4%/yr, compared to over 6%/yr during the previous 10 years. The combined share of buses and rail declined to 3.9% from 4.5%, a share which had changed very little since 1970.

One potentially important change is the drop in the ratio of automobile and household light truck kilometers driven to GDP or household incomes (Davis, 2000; DOT, 2000). While this indicator was roughly constant in the 1980s and early 1990s, it started to fall in 1994, and that fall continued after 1998, driven perhaps by higher fuel prices in 1999 and 2000. Whether this signals a permanent change in the use of cars—a sign of saturation—may become clearer in the near future as the year 2000 Personal Travel Survey is released.

Fig. 3 depicts trends in modal energy intensities. Intensities for all modes except air travel have changed relatively little. Intensities as we have defined them are a factor not only of the technical efficiency of the mode (i.e. energy consumed per tkm of mass moved) but also of changes in the mass and size of the vehicles and the average load factor. Thus, as Fig. 3 shows, average auto and light truck *vehicle* intensities declined at a faster rate than passenger intensity between 1988 and 1991. This is largely due to the fact that the average load factor fell 2% between those years. The load factor continued to decline, but leveled off after 1995. Another factor that has worked to increase auto/light truck modal intensity during the study period is the growing share and size of light trucks (including sport utility vehicles and minivans) in the new car fleet. The share of light trucks in the 1998 new car fleet was 44.5% compared to 30.1% in 1988. At the same time the average weight of new passenger cars increased from 1285 to 1396 kg (NHTSA, 1999). Average new passenger car fuel economy was slightly lower in 1998 at 8.20 l/100 km compared to 8.17 l/100 km in 1988. The decline in average fuel economy was even greater for light trucks, 11.05 l/100 km in 1988 compared to 11.26 l/100 km in 1998. The decline in fuel economy for light trucks combined with their growing share in the total fleet pulled the total average new passenger fleet economy down from 9.05 to 9.57 l/100 km.

As would be expected, bus and rail modal energy intensities are significantly lower than those for air and car travel.[3] However, Fig. 3 reveals an interesting surprise. In the US the energy used per pkm for commercial air flights is slightly *less* than that required to move 1 pkm by cars and light trucks. This was not the case until the mid-1980s. Between 1970 and 1985 the

[3] This is not true for city busses, which use approximately the same (or even more) energy per pkm than cars because the buses have very low load factors (Davis, 2000).

Box 1
Travel sector definitions of indicators

Subsectors/end uses: Passenger cars and light commercial vehicles used for private travel, buses, domestic rail and subway/trams, and domestic air travel.
Activity: Travel measured in passenger-kilometers (pkm), and vehicle-kilometers (vkm) for some indicators concerning cars.
Structure: The shares of total travel (in pkm) accounted for by each of the modes.
Intensity: Vehicle intensity is energy use/vkm; modal intensity is energy use/pkm.

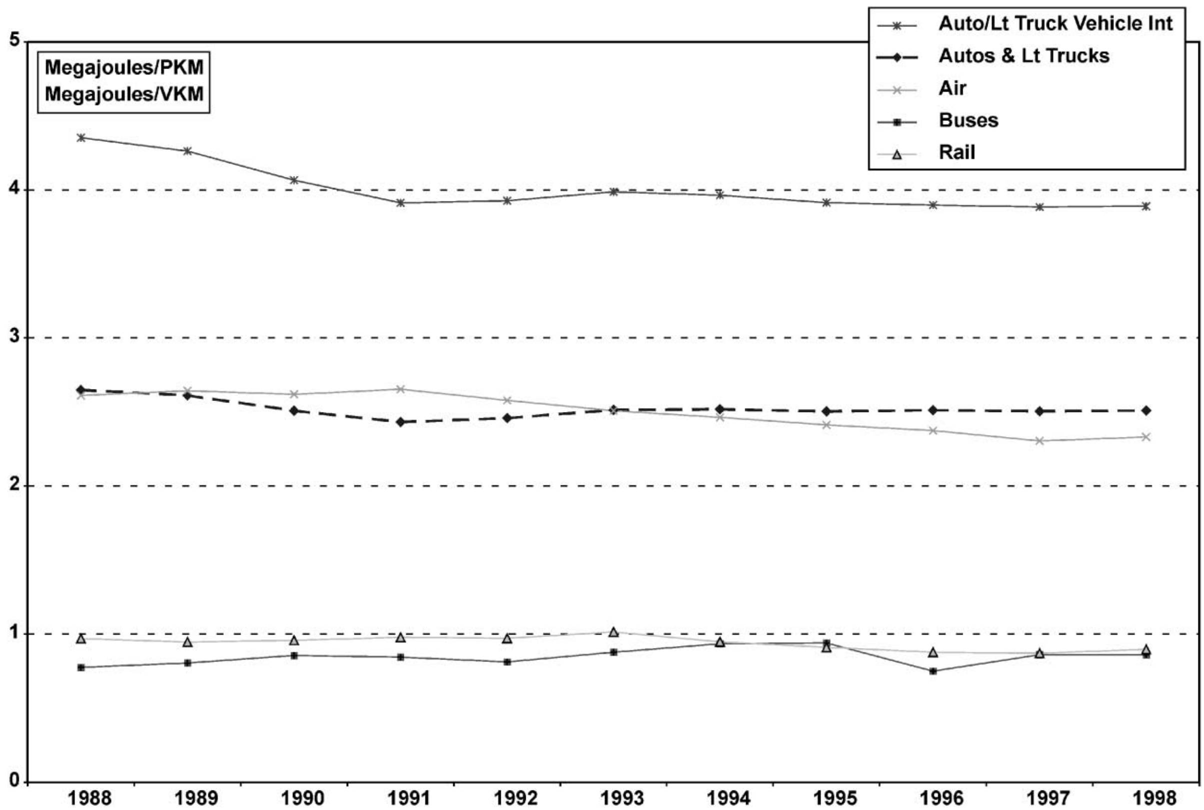

Fig. 3. Travel energy intensities by mode.

energy intensity of air travel fell by nearly a half, the result of technical efficiency improvements and increases in both the load factor and average plane size. Meanwhile, the combined modal energy intensity of autos and light trucks has changed very little since 1990.

Fig. 4, which shows the results of the decomposition of the travel sector, depicts the impact that each of the decomposition terms has had on travel energy use since 1988. The decomposition terms may be thought of as representing the counterfactual amounts of energy that would have been used if only the characteristics measured by that term had changed while the others remained the same. The index of actual energy use in a given year equals the product of the other indices. The activity line shows what effect total pkm has had on energy use in this sector. Increases in total travel activity have predominated in influencing energy use over this time span. The virtually flat line showing the effect of structural changes may be surprising given some significant trends in modal shares, such as the growth in share of air travel. However, air and auto travel in the US have roughly equal energy intensities so the shift in shares has little effect on energy use. The *relatively* large loss in travel share for buses and trains has also had an imperceptible effect on total energy use since these two modes account for so little of the pkm traveled and even less of the energy consumed. What is clear from Fig. 4 is the importance of intensity reductions in restraining energy use. Between 1988 and 1991 energy use declined substantially, even as travel activity increased. Then as intensity changes leveled off in the 1990s, energy use increased 23% over the next 7 yr.

3.2. Freight

Freight energy use passed over 7000 PJ in 1998, or about 12% of the delivered energy consumed in the US that year. The freight sector has been the fastest growing

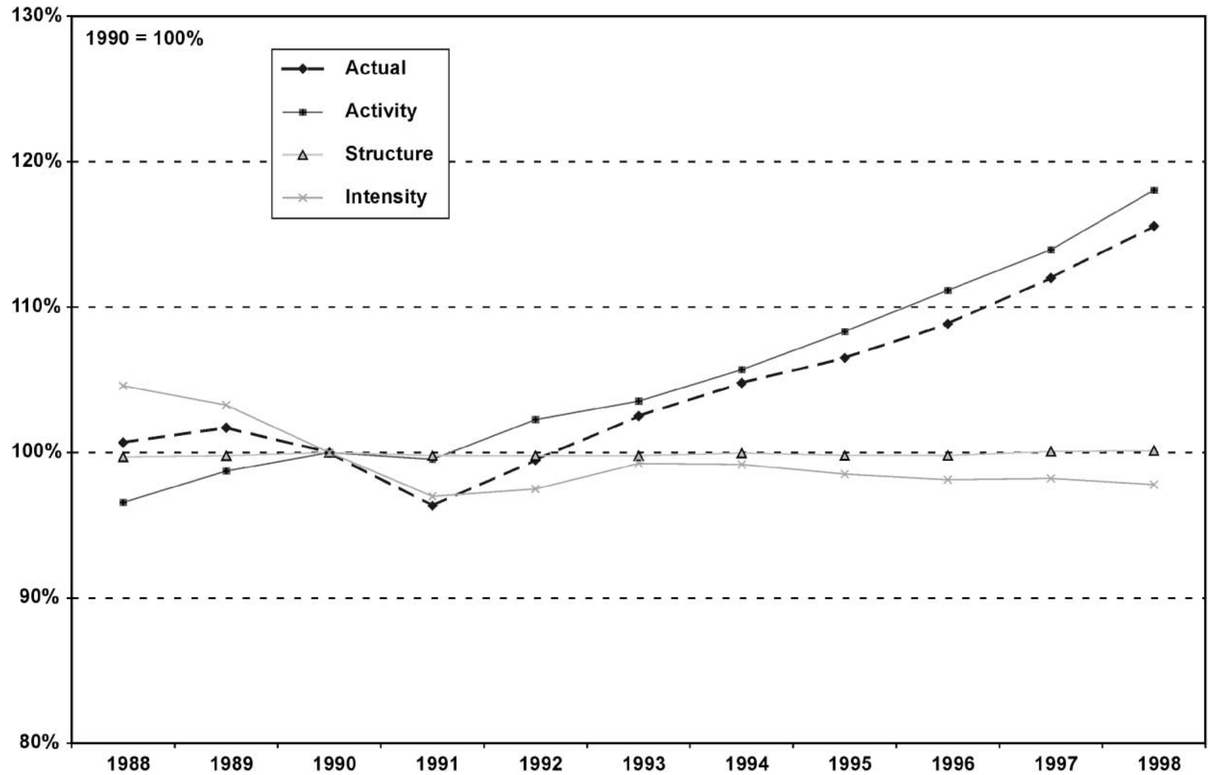

Fig. 4. Travel sector energy use, actual and decomposition effects.

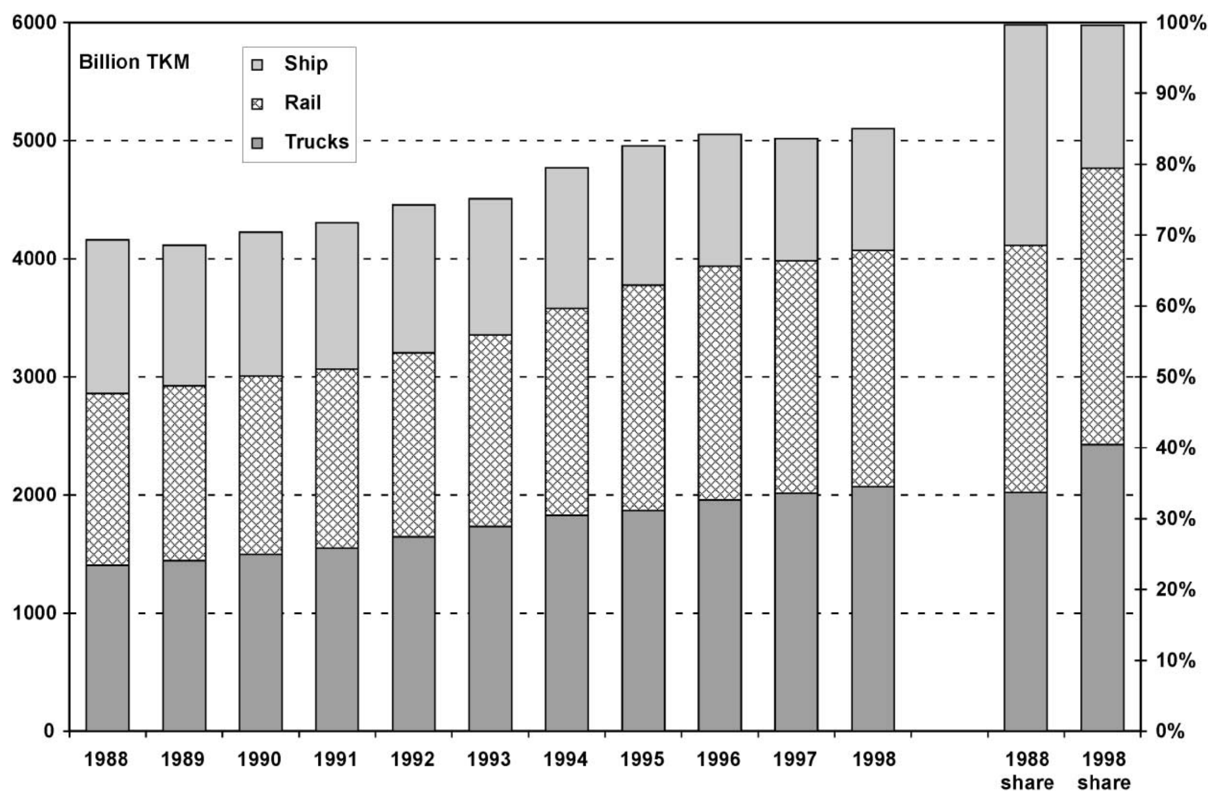

Fig. 5. Total freight activity by mode, with 1988 and 1998 shares.

Box 2
Freight sector definitions of indicators

Sectors/End uses: Freight light and heavy trucks, domestic rail, domestic air, and domestic shipping and barges. (Pipelines are excluded.)
Activity: Freight haulage measured in metric ton-kilometers (tkm).
Structure: The share of freight hauled in total tkm by each of the modes.
Intensity: Modal intensity is energy use/tkm.

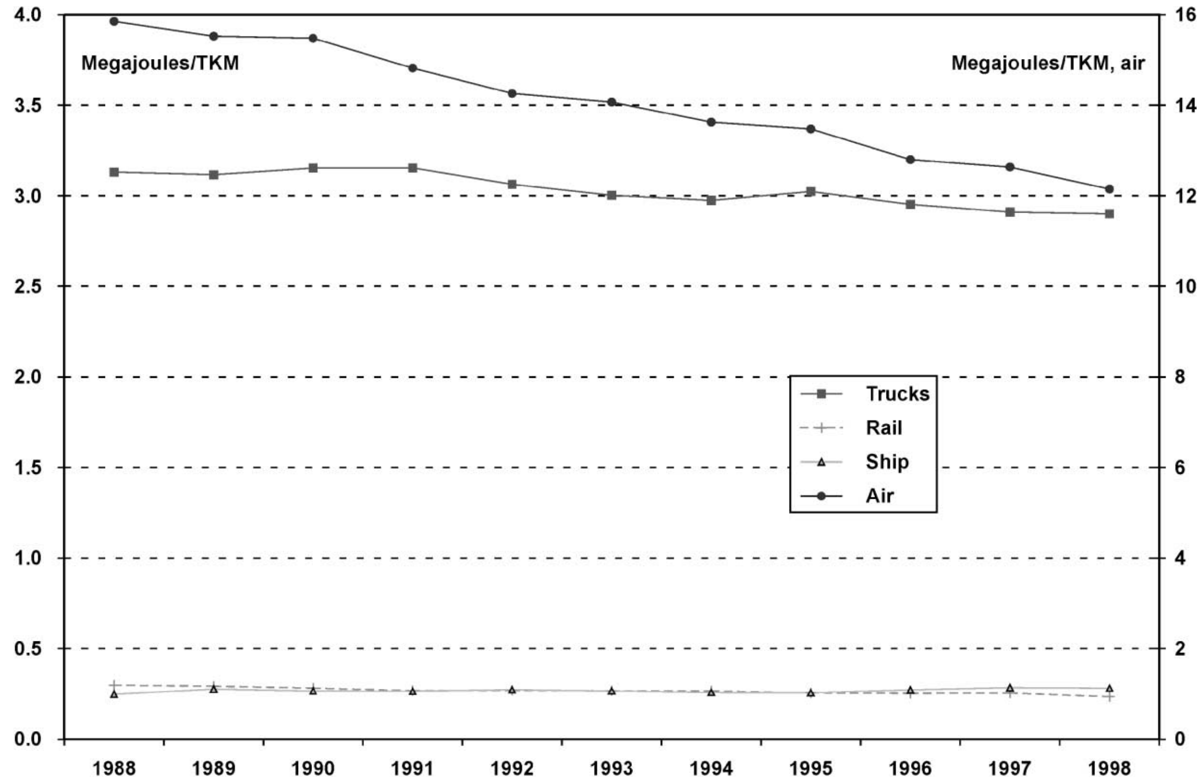

Fig. 6. Freight energy intensities by mode.

energy consumer over the study period, largely due to the rapid growth in freight activity. By 1998 total freight activity increased about 23% to over 5 trillion tkm. Fig. 5 depicts the total trend in freight activity, as well as the breakdown by each mode. Air freight is not shown, since it carried less than 0.5% of the total in all of the years studied.

Total energy use, however, increased more than the growth in activity—about 31%. Changes in the modal shares (Box 2) toward more energy-intensive trucking contributed to the increase in energy use. The last two columns in Fig. 5 show the shares of total tkm carried by each mode. This reveals that trucking continued to capture a larger market share of total freight hauled in the US, mostly because of changes in the type of freight hauled. Rail held share, at the expense of shipping, since these two modes compete for bulk shipments.

While both structural changes and total activity growth acted to substantially boost energy use, declining energy intensities played a large role in helping restrain it. Intensities declined for every mode but ships, and most significantly for air freight (see Fig. 6). However, since air freight carries such a small share of the total tkm, the decline in rail and trucking intensities had the largest effect on decreasing energy use in the sector. In relative terms rail intensity declined the most—over 20%. Trucking intensity declined less—roughly 7%, but since these two modes combined carried almost 80% of the 1998 domestic freight, this led to substantial energy savings. The reasons for the decline in energy intensity for the two modes differ. For freight trains the energy consumed per rail car-kilometer fluctuated around an average of about 10 MJ/ckm. However, the average load per car increased from 34.3 to 38.6 metric tons. The converse was true for trucks. While average metric tons per vehicle remained relatively unchanged, the energy intensity dropped from 9.3 to 8.4 MJ/vkm.

The decomposition in Fig. 7 reveals that the shift toward trucking increased the demand for energy enough to offset the nearly 10% decrease that would

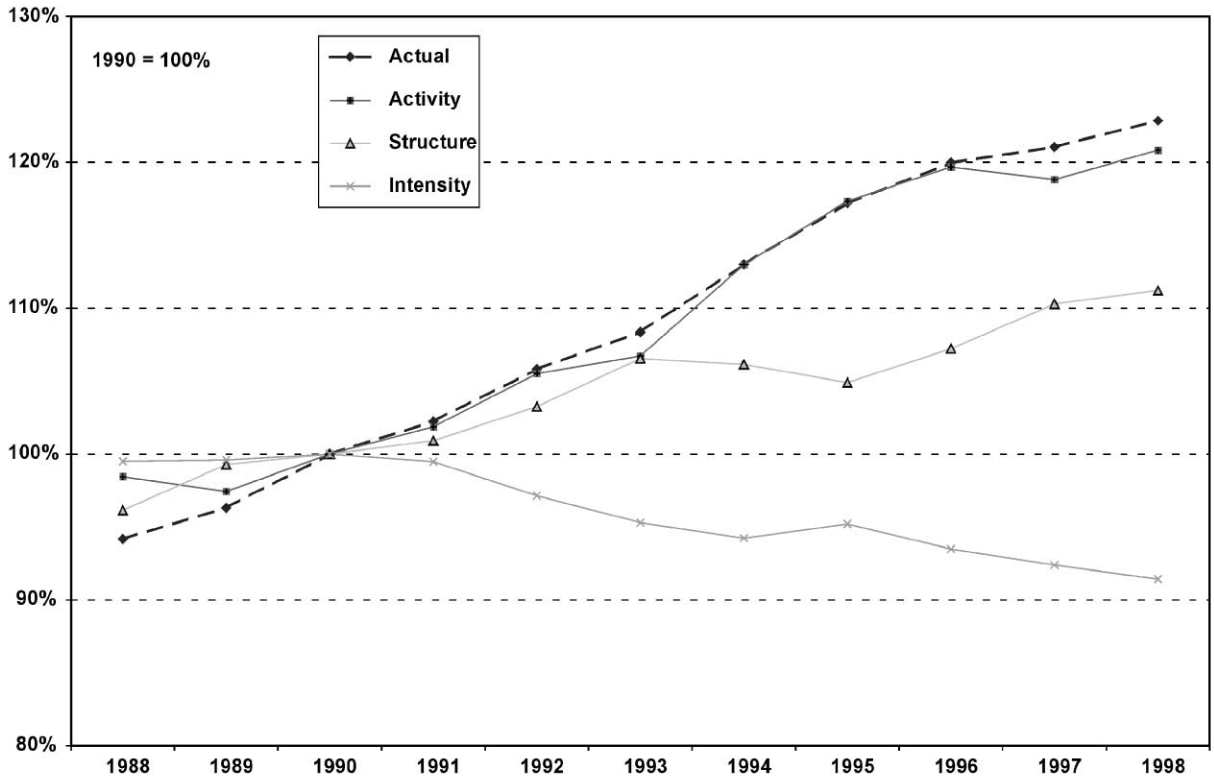

Fig. 7. Freight sector energy use, actual and decomposition effects.

have otherwise resulted from changes in modal energy intensities. The sheer growth in total freight activity was the single largest determinant of changes in freight energy use. Since intensity and structural indicators largely offset each other, changes in actual energy use tended to coincide closely with changes in total freight activity.

3.3. Manufacturing

The manufacturing sector consumed over 14,300 PJ of delivered energy in 1998, or about a quarter of the national total.[4] This was up from 12,360 PJ in 1988, an increase of about 16%. Oil and coal both lost energy share to the other sources. Coal share dove from 21% to 16% of delivered energy consumption, while the relative gains in share for gas, wood, and electricity were about equal. Due to the large primary energy losses associated with generating and delivering electricity, the increasing share of electricity resulted in a greater jump in primary energy consumption—almost 19%.

Overall, increasing energy consumption was driven mostly by the sharp increase in manufacturing value added between 1992 and 1998. During the recession from 1988 to 1992 both energy consumption and manufacturing output stagnated. Then between 1992 and 1998, real manufacturing value added increased 34%.

Fig. 8 reveals that the structure of the manufacturing sector (Box 3) changed rapidly in the 1990s. Important structural shifts occurred both as light industries gained relative to heavy industries, and as shares shifted within these two categories. Light manufacturing industries (food processing and miscellaneous industries) gained some market share despite a fall in real value added for food processing. Miscellaneous manufacturing industries grew the most over this time period, primarily due to the explosive growth of the "electronics and other electrical products" branch. Growth in this and other of the miscellaneous industries compensated for the stagnation in value added in food processing. This is an important trend in reducing the overall energy intensity of the sector as a whole, since the average energy intensity of the heavy industries in 1998 was about 34 MJ/$ compared to 5 MJ/$ for the light industries. Thus, as light industries account for a larger share of manufacturing value added the aggregate intensity of the sector declines.

Another important change has occurred within these two broad categories of manufacturing branches. Within the heavy manufacturing sector both non-metallic minerals and non-ferrous metals grew faster than the others while the value added in pulp and paper changed

[4] These figures are much lower than the "first use of energy" totals given in MECS, which is roughly 24,000 PJ for 1998. Our exclusion of energy sources used as feedstocks accounts for over 7000 PJ while delivered energy consumed by refineries accounts for the rest.

Box 3
Manufacturing sector definitions of indicators

Subsectors/End uses: Manufacturing is disaggregated into seven subsectors:
Paper and pulp (NAICS 322),
Chemicals (NAICS 325),
Non-metallic minerals (NAICS 327),
Iron and steel (NAICS 3311 and 3312),
Non-ferrous metals (NAICS 3313 and 3314),
Food and kindred products (NAICS 311),
Other manufacturing industries (all remaining sub-sectors of NAICS 31-33, excluding refining).

Activity: Contribution to GDP from manufacturing industries, here termed value added, measured in real 1990 dollars.
Structure: Mix of manufacturing output, measured as relative shares of value added among the subsectors. Terms are additive to total GDP in manufacturing.
Intensity: Delivered (final) energy use per value added for each subsector. Energy intensity is measured in terms of economic output because of the near impossibility of accurately measuring the energy intensities of individual manufacturing products over long periods. Additionally, using value added facilitates comparability across manufacturing branches and among thousands of intermediate and final products.

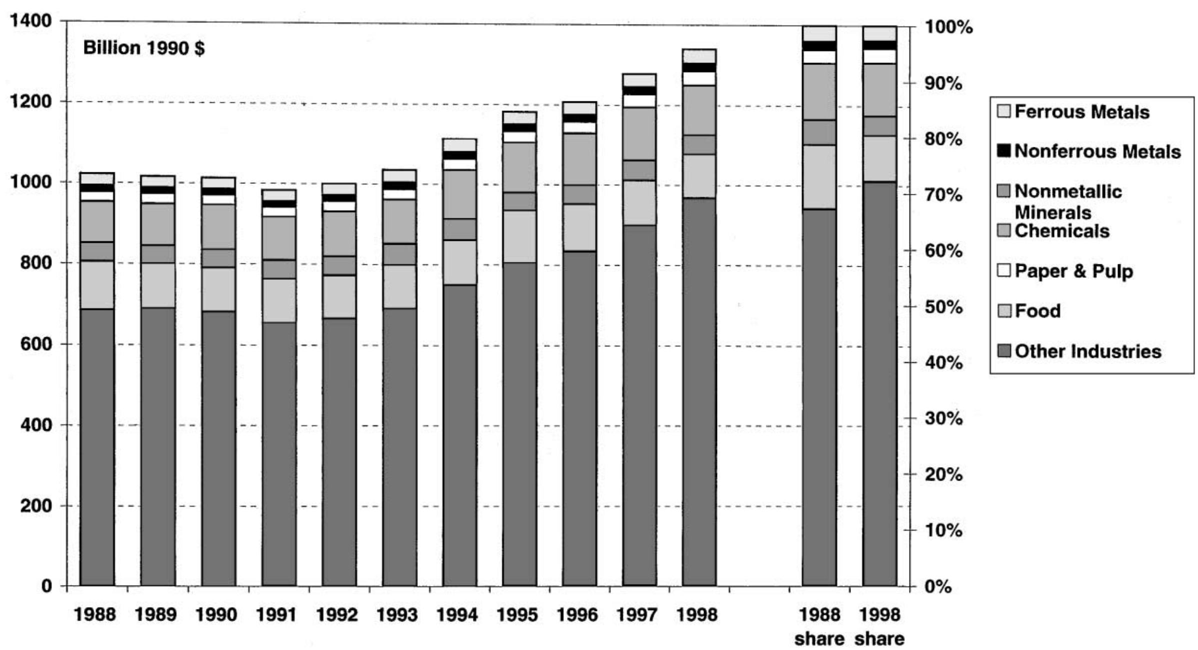

Fig. 8. Manufacturing value added by industry branch, with 1988 and 1998 shares.

relatively little. Fig. 9 shows the individual energy intensities of the six manufacturing branches and the grouping of miscellaneous light industries. Since non-metallic minerals and non-ferrous metals are roughly half as energy-intensive as paper and pulp, the shift in shares from between these industries has contributed significantly to the overall structural trend toward lower aggregate energy intensity. Among the light industries, the fact that miscellaneous industries' share of light manufacturing value added increased from 85% to 90% also contributes to a structural dampening of energy demand.

Energy intensities within certain branches have changed markedly over the study period. Three energy-intensive industries experienced sharp declines in energy intensity. The largest relative decline occurred in non-metallic minerals with 1998 intensity 38% lower than in 1988. Ferrous and non-ferrous metals both experienced declines of about 30%. New process-control technologies may have contributed to the substantial energy savings in these branches, but this may also be due to shifts toward greater use of recycled materials, a structural change below the level of disaggregation that we can measure. Since these three industries combined consumed about a quarter of the 1988 manufacturing delivered energy, the decline in intensities resulted in significant energy savings. However, intensity increased in both chemicals and paper and pulp—two industries

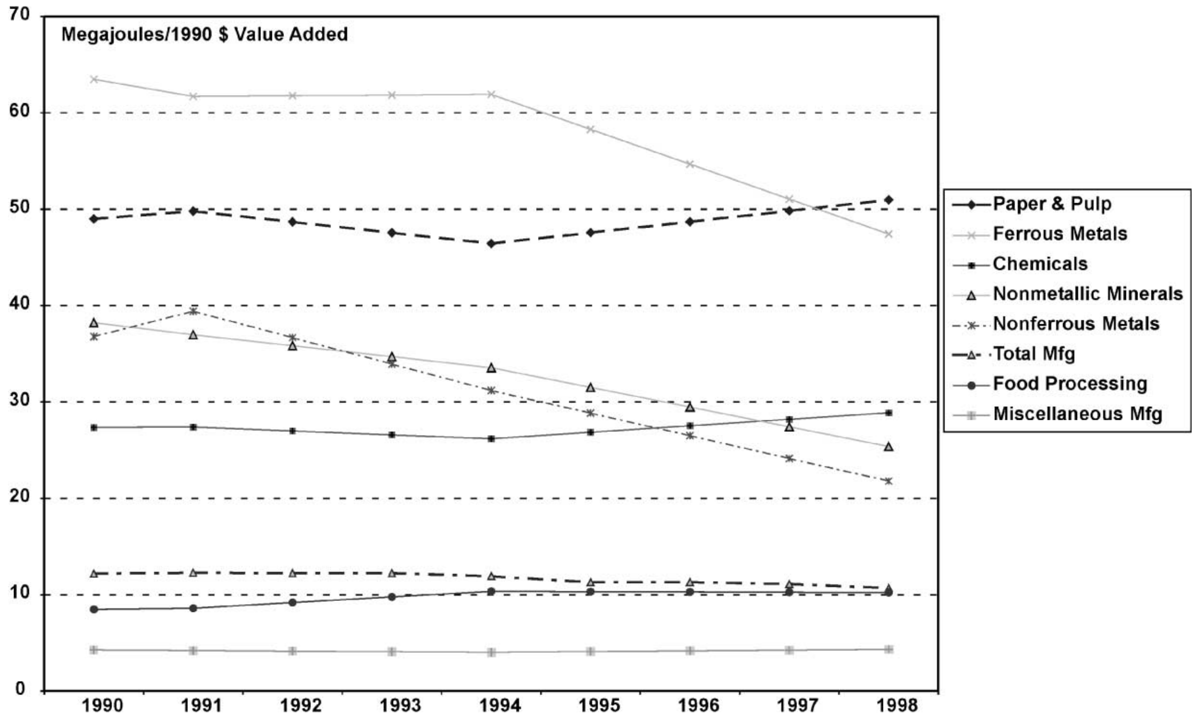

Fig. 9. Manufacturing energy intensities, total and by branch.

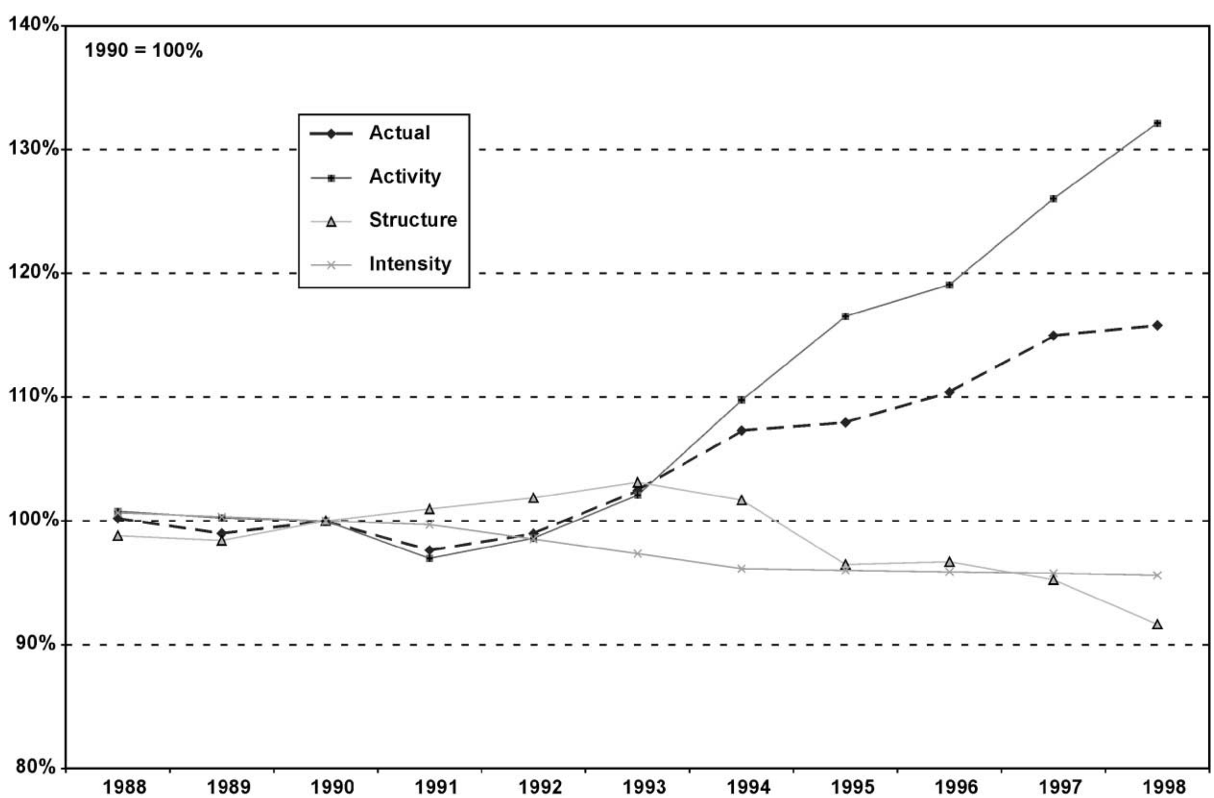

Fig. 10. Manufacturing energy use, actual and decomposition effects.

that together consumed over 40% of total delivered manufacturing energy in 1988. Energy intensity also increased significantly in the food processing industry.

The "total manufacturing" line in Fig. 9 reflects the combined effects of changes in structure and individual branch energy intensities. Overall, aggregate intensity fell 12%. However, this decline occurred entirely after

Box 4
Residential sector definitions of indicators

Subsectors/end uses: Residential space heating, water heating, cooking, six major appliances, miscellaneous appliances, and lighting.
Useful energy: As an approximation of the amount of heat that emanates from a space heater, boiler or furnace to a house or to water. Equal to delivered energy in electricity, 66% of delivered energy of gases and liquids, and 55% of delivered energy in coal, wood or other solids. It is important to differentiate between useful and delivered energy so that fuel switching for certain end uses does not appear as an energy savings when a real decline in intensity has not occurred.
Activity: Population.
Structure: Per capita dwelling area for space heating and lighting, index of square root of average number of occupants per dwelling for cooking and water heating, per capita appliance ownership.
Intensity: Useful energy and delivered energy use per square meter per degree-day for space heat. Energy per capita for water heating and cooking. Annual energy consumption by type of appliance. Lighting energy per square meter of floor area.

1993. To what extent is this decline due to structural vs. intensity changes? The decomposition shown in Fig. 10 depicts how these two underlying factors each affected the aggregate intensity shown above.

The decomposition in Fig. 10 makes it clear that increasing activity has been the greatest single driver of energy use in the sector. However, trends affecting the *aggregate* intensity of the sector have helped to restrain energy demand. Until 1991 neither structural shifts nor branch-level intensity changes had much effect on energy use. Between 1991 and 1994 energy intensities declined while the structure of US manufacturing became increasingly energy-intensive to 1993 before falling again in 1994. Since 1994 the combined effect of intensity changes across all branches has resulted in virtually no additional energy savings. As discussed above, impressive declines did occur in the energy intensities of metals and minerals transformation, but these were offset by increases in the energy intensities of chemicals, paper and pulp, and food processing. At the same time, structural changes have had the effect of pulling energy use down by about 10%, and this effect has been predominant in reducing energy use since 1994.

Since the refining industry is classified as part of the energy-transformation sector by many OECD member countries we have studied, we have excluded it from this analysis. However, with a 1998 energy intensity of nearly 120 MJ/$, refining is by far the most energy-intensive industry, and its value added is comparable to that of the other heavy industries. In all, when included as part of the manufacturing sector it accounted for about 19% of delivered energy consumed for manufacturing in 1998. Inclusion of this industry can thus have a large impact on the analysis of the manufacturing sector. While including refining raises aggregate manufacturing intensity by 20% to 25% in any given year, over the study period it has had a minimal effect on the aggregate intensity trend. However, refining strongly affects the decomposition by enhancing the predominance of the structure effect. The fact that the refining industry value added share fell from 3.4% to 2.0% while its intensity increased (principally between 1988 and 1992) results in a 14% decline attributable to structural change while intensity changes *increase* energy consumption by 3%.

3.4. Residential

Energy use grew less in the residential sector than in any other. Corrected for climate, delivered energy only increased 6% from 1988 to 1998. This is less than the 10% increase in population, implying that intensity trends have helped to reduce the amount of residential energy consumed per capita. Uses of oil products and wood declined significantly while consumption of gas and electricity grew. This led to an increase in the combined shares of electricity and gas from 74% to 80% of residential energy demand. The increase in the share of electricity had a large impact on growth in total primary energy consumption, which increased 18%.

When normalized to population, energy use has changed relatively little since 1988, declining by about 4%. Fig. 11 shows that space-heating energy per capita has declined, but energy used for other purposes has increased, most notably for water heating and "other" appliances. The increasing energy use attributed to "other" appliances would be expected as ownership of relatively novel appliances and electronic products continues to progress. For example, according to official data from RECS, microwave oven ownership increased from 63% of all households in 1987 to 81% of households in 1997 while personal computer ownership jumped from 16% in 1990 to 35% in 1997. Changes in "other" appliances may also occur due to inaccuracies in accounting for the other end uses of electricity, since the energy consumption attributed to this category is the residual of what is left after the other uses have been subtracted from the total. The increasing consumption attributed to water heating, however, is less obvious. This is due mostly to the recorded increases in intensity for oil and gas fired water heaters. It is possible that this increase is due to mostly to sampling error.

Fig. 11 indicates that space heating alone accounted for about 50% of total residential energy use in 1998, down from 57% in 1988. Two factors helped to reduce

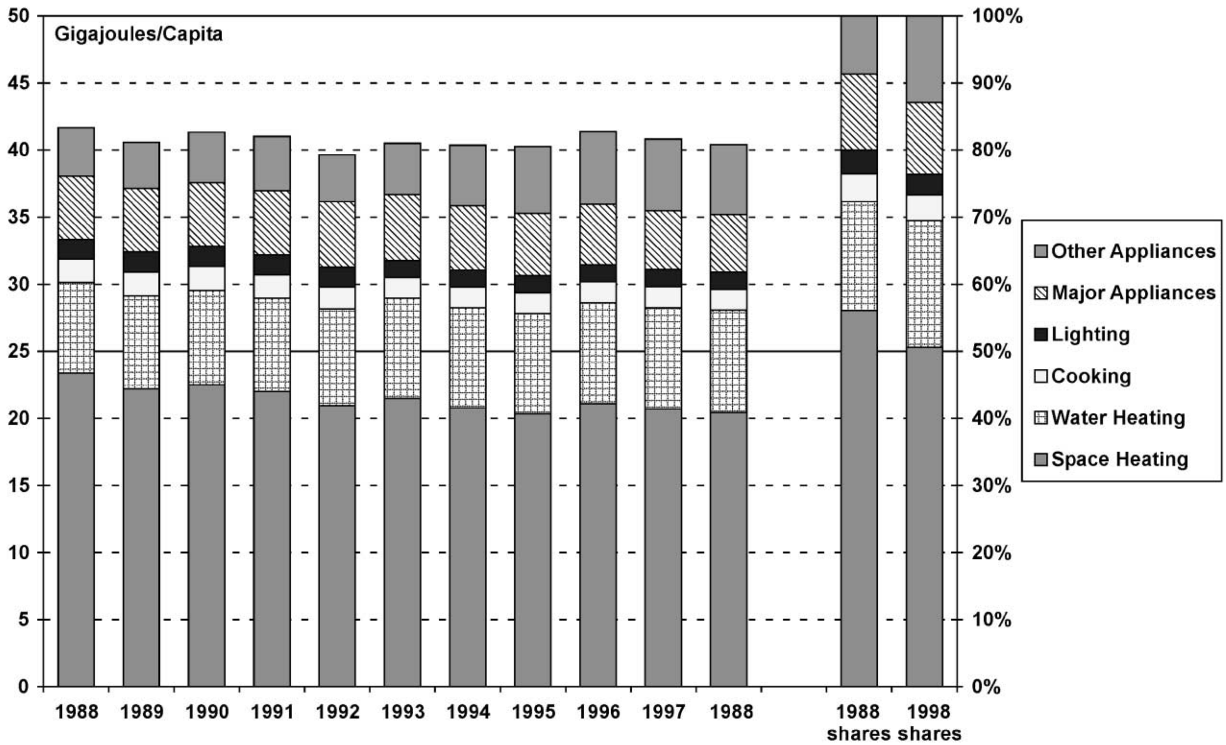

Fig. 11. Residential energy use per capita by end use, with 1988 and 1998 shares.

space heating energy requirements per capita. Most importantly, according to calculations from RECS data, space heating intensity (Box 4) declined by nearly a quarter between 1988 and 1998. A much smaller factor in savings of delivered energy is the increasing saturation of electric heating. Electricity "saves" energy because it is much more efficiently transformed into useful heat, whereas a third to almost half of the potential energy in petroleum products or gas is lost as waste heat or through incomplete combustion. Therefore, the increasing share of electricity for multi-fuel end uses has contributed slightly to reducing demand for delivered energy. However, due to the large transformation and distribution losses associated with the use of electricity, electric heating uses more primary energy per unit of useful heat.

The savings in heating energy were important in offsetting a significant structural change. Home floor area is a key driver of space heating, cooling, and lighting, and Americans enjoy large home sizes relative to other OECD countries.[5] The average amount of dwelling space per capita has been rising continuously except for a brief period in the early to mid-1980s when per capita home size remained level. Per capita dwelling area, which is growing less rapidly with respect to the measure of income, personal consumption expenditures, appears to be reaching saturation. This is an important structural change that reduces the heating needs of the country, relative to GDP. Still, the average size of dwellings continued to increase as average size of new homes expanded and older, smaller homes were retired from the stock. These two factors resulted in an increase of 15% in the average dwelling space per capita. Coupled with population growth, this means that total heated dwelling space increased by over a quarter.

Trends for the other multi-fuel end uses, namely cooking and water heating, have shown little change in recent years. Our structural indicator, the inverse of the square root of the average number of occupants per dwelling, has resulted in a negligible increase in per capita demand for energy services. Data for cooking are particularly questionable in terms of accuracy, and several factors may influence our indicator for cooking intensity. The use of microwaves, for which RECS provides no energy use estimates, are lumped in with other appliances. As more households acquire microwaves this would have the effect of reducing per capita energy use from ranges and ovens. As with space heating, the shift toward greater use of electricity also helps reduce the demand for final energy, but this would

[5] In 1997, US dwelling size per capita was 58 m^2, compared to 54 m^2 in Sweden, 41 m^2 in Canada, 35 m^2 in France and the UK, and 33 m^2 in Japan.

Table 1
Unit energy consumption in kWh/yr and saturations of major appliances in the stock

Appliance	Unit energy consumption in kWh/yr		Saturation, % households with appliance	
	1988	1998	1988	1998
Refrigerators	1212	917	114%	115%
Freezers	1108	680	36%	36%
Washers	105	102	75%	77%
Dryers	957	898	52%	55%
Dishwashers	166	148	44%	51%
Air conditioners	1771	1673	65%	72%

not affect our intensity indicator, which is measured in useful energy. Behavioral factors also play a role since changes in the number of meals eaten away from the home would also have an impact. It is probably these factors that resulted in a decline in the useful energy per capita of about 17%.

Appliances consumed almost a quarter of the final energy in 1998, up from about 20% in 1988. Some structural indicators suggest that in the future appliances may not generate the same rate of demand for electricity as they have in the past. Table 1 lists the 1988 and 1998 saturation figures for six major appliances. Among these appliances, the average annual rate of growth in saturation has been slower in the 10 yr between 1988 and 1998 than during the preceding 10 yr. Saturation levels remained virtually unchanged for refrigerators and freezers, while saturations of washers and dryers experienced only slight growth. The only appliances that have apparently not yet reached nearly complete saturation are air conditioners and dishwashers.

Table 1 also provides an overview of the changes in the unit energy consumption of major appliances. While an increasing number of households and a larger number of appliances per household were two factors creating upward pressure on appliance energy consumption, individual appliance intensities largely offset these two factors. The largest savings, both in relative and absolute terms, came from intensity declines for refrigerators and freezers. Of the more than 58 TWh of electricity saved in 1998 from major appliances, almost 60% of that was from refrigerators alone. In relative terms dishwashers were the only other appliance group for which intensities fell appreciably. Washing machine intensity fell the least, but since washing machines are not very energy-intensive, there may simply not be much energy to save.

The decomposition results for the residential sector provide some interesting results (Fig. 12). Since activity is defined as population, the upward pressure on energy use from this indicator has been, as would be expected, steadily increasing. Population growth alone would have increased energy use by about 10%. This upward pressure on energy use was augmented by an almost identical impact from structural changes, which would have increased energy use by 9.5%. The rate of growth in the structure term has changed little since the 1980s but is slower than the 1970s, when many households were still acquiring dryers and air conditioners. Over 80% of the increase attributed to structural changes during the 1988–98 period is due to the impact of increasing dwelling areas on space heating demand, with increasing penetration of air conditioners accounting for the next largest share at around 6%. Energy savings from changes in intensities totaled about 10% in 1998. Virtually all of this saving was due to rather dramatic declines in space heating intensity, with some contribution from refrigerators and freezers.

The miscellaneous electricity category is difficult to analyze. Surprisingly, however, we find no bulge in electricity that could be associated with home use of electronics. This is consistent with findings presented by Kawamoto et al., 2001.

3.5. Services

The service sector, accounting for about 13% of 1998 final energy use, is a relatively small final energy consumer, although the 17% increase in energy consumption was slightly more than the average for all sectors. The growing share of electricity had a tremendous impact on primary energy consumption, which increased 32% (for detailed study of this sector, see Krackeler et al., 1998). By 1998 electricity represented about half of the final energy consumed. Due to the high utilization of electricity, this sector consumed a much higher share of 1998 primary energy—almost 20%. Although this sector consumes a relatively small share of delivered energy, its rapid increase of primary energy makes it an important sector for study.

With service sector value added growing 37% to over \$5.3 trillion, activity was the largest single driver of services energy use. At the same time that increases in services activity have been driving energy use up, the structural indicator (Box 5) has compensated to some degree as services floor area has not kept pace with the growth in services value added. This has been particularly true since the economic boom between 1995 and

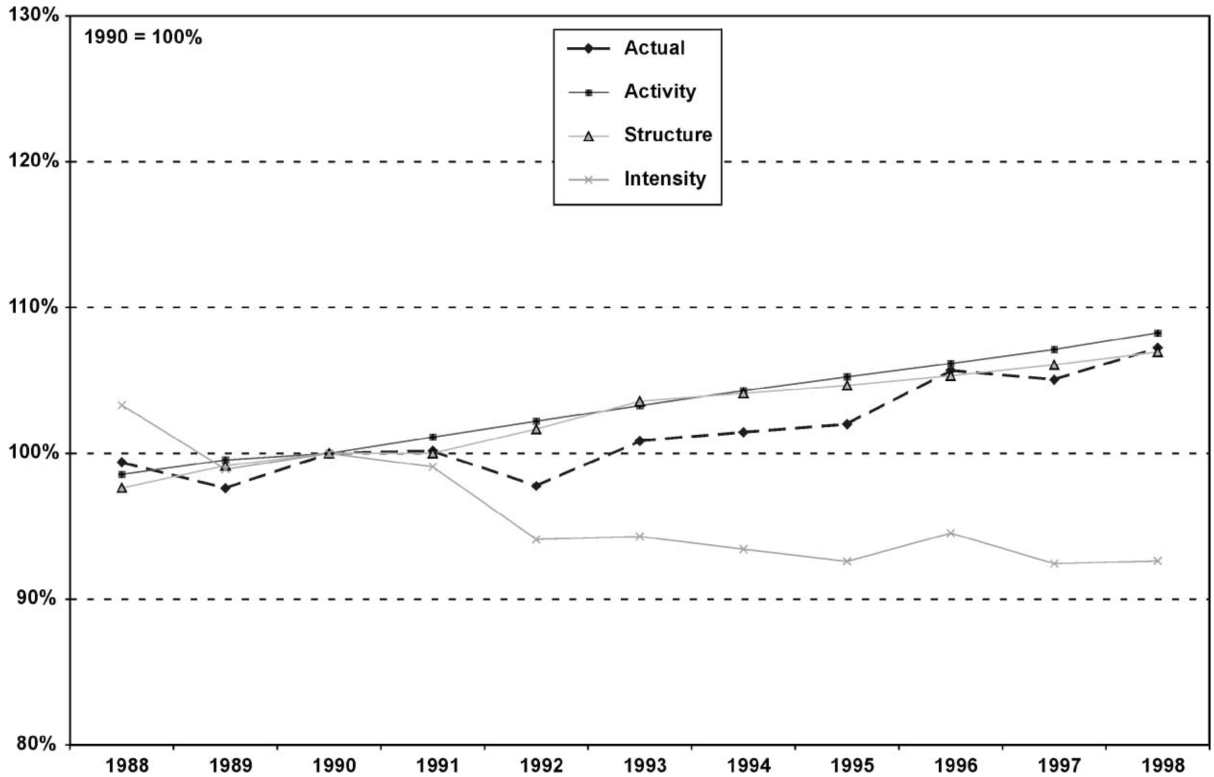

Fig. 12. Residential energy use, actual and decomposition effects.

Box 5
Service sector definitions of indicators

Composition: This sector consists of NAICS categories 4–9.
Activity: Value added arising from the sector measured in real 1990 dollars.
Structure: Floor area per real dollar (1990) of services value added.
Intensity: Delivered (final) energy use per floor area. This can be split into electricity and other energy forms for some purposes. Primary energy intensity is also used.

1998 when the annual growth in services value added averaged over 5%. Between 1988 and 1995 the structural indicator fell slightly from 1.48 to 1.44 m^2/\$1000. By 1998, however, this number fell another 10% to about 1.29 m^2/\$1000.

The service sector has not experienced much change in energy intensity. While intensity did initially decline between 1988 and 1992, intensity actually increased by nearly 7% by 1997 before falling slightly in 1998. However, there is an important difference in the trends between fuel consumption and electricity consumption. While total final energy consumption per square meter remained virtually unchanged, fuel intensity declined by about 14%. Since most of this energy is used for space heating, it would appear that average heating efficiency may be improving. On the other hand, electricity intensity *increased* by 14%. This increase would be expected as computers and other electronic equipment became more prevalent in offices and educational buildings. What is remarkable is that as more floor area is heated by electric space heating and as more electronic equipment is used, electricity intensity has not increased more. This is consistent with the findings of Kawamoto et al. (2000). Further analysis when the next Commercial Building Energy Consumption Survey (CBECS) appears will doubtlessly shed more light on these developments.

A decomposition analysis shows that the service sector is an extreme example of the predominance of structural changes in reducing energy use in the 1990s. Actual energy use in the services sector grew more than in any other sector except freight. Activity growth was the main driver of changes in energy use in this sector. Intensity did not have much impact overall, as the decline in the first few years were negated by increasing intensities after 1992. Since the increases are due to increasing electricity per square meter, this may largely be the result of greater use of computers and other electronic equipment. The structure effect, particularly after 1995, helped to offset the upward pressure on energy use.

One important caveat is that there are significant concerns regarding the official CBECS data for floor

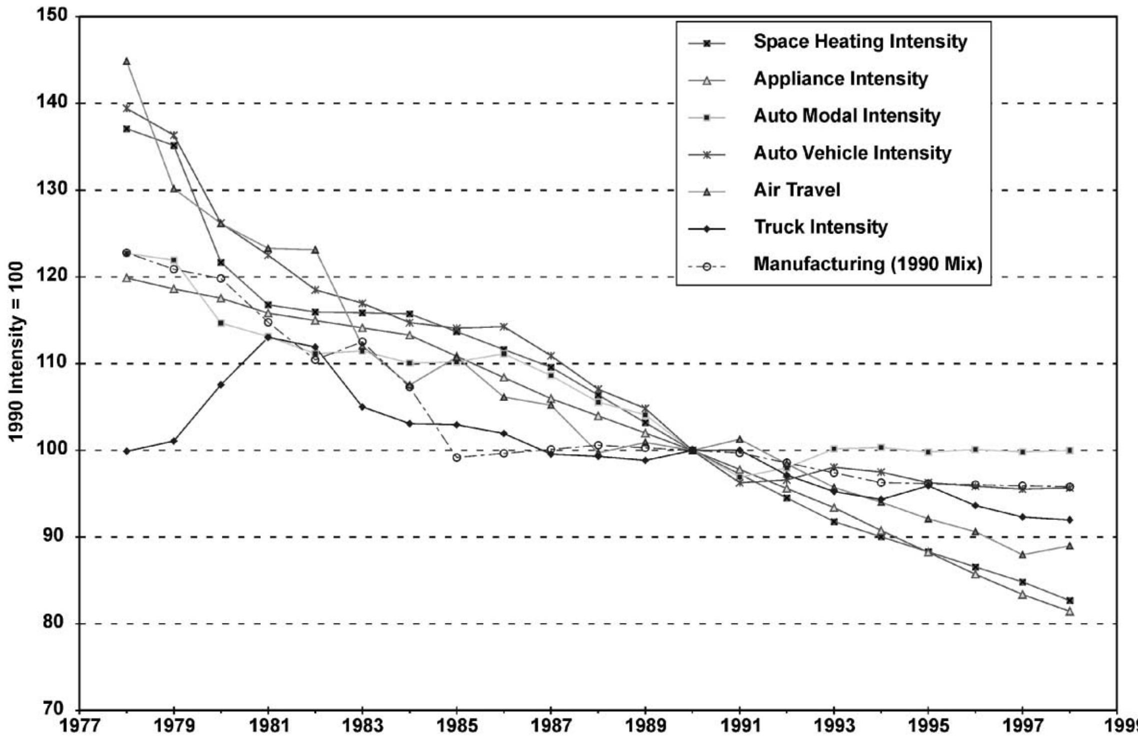

Fig. 13. Energy intensities of key end uses.

area. We have used a time series developed at Pacific Northwest National Laboratory, which we have updated using new construction data from FW Dodge as reported in the Statistical Abstract of the United States. Our series diverges sharply from CBECS after 1992 due to the fact that the 1995 CBECS reports a 9% drop in total floor area, even after adjustments are made to the 1992 figure to correct for a change in the survey population. This reported decline has an enormous impact on the structural and intensity indicators. While it is unlikely that a 9% drop in services floor area coincided with an 8% increase in value added from 1992 to 1995, the difference in the spot estimates provided by CBECS is not statistically significant.[6]

4. Changes in total energy use

We examine the entire US economy in three steps. First, we compare key indicators of particular end uses: how did energy intensities and energy service levels change? Then we combine the sectoral decomposition results to give an overall measure of changes in US energy use and how those changes compare with GDP. Finally, we comment on the nature of the changes and possible links to the so-called information economy.

4.1. Changes in key energy intensities and energy service levels

The changes in some key energy intensities since 1978, indexed to their 1990 values, are depicted in Fig. 13. The energy intensities of most of the end uses we have studied fell rapidly from the early 1970s until the late 1980s, led by air travel and space heating. After the fall in real energy prices in 1985 many intensities began to fall less rapidly. Of particular interest is the slower decline in the 1990s of automobile and manufacturing intensities, since these two energy uses led the decline in total energy use per GDP in the 1970s and 1980s.[7]

Fig. 14 shows the complementary energy service indicators for the end uses shown in Fig. 13. For each end use, this indicator measures the rate of growth in the activities that consume energy relative to the rate of growth in GDP. Altogether, these indicators comprise the energy services per GDP effect. Contrasting the two indicators shows some interesting results. For example, while air travel intensity fell rapidly from 1978 to 1998, the number of air pkm traveled per unit of GDP has increased. By 1998 the energy used for air travel per unit of GDP was slightly higher than in 1978. With the

[6] For a discussion of the statistical issues surrounding the apparent decline in commercial floor area, see DOE, 2000.

[7] Travel intensities as defined here are the amount of energy consumed per passenger-km (pkm) moved. Since the average number of passengers per automobile has declined this has caused the energy intensity of this mode to fall less rapidly than the technical efficiency of the vehicles. The opposite is true for passenger air travel.

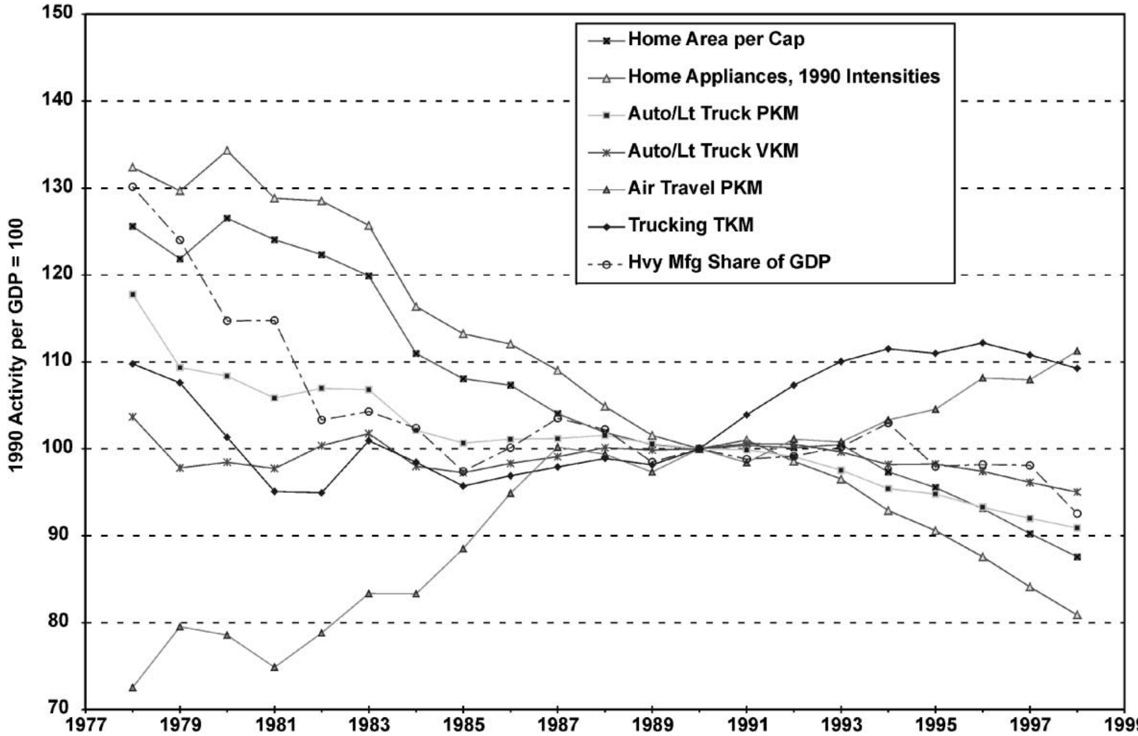

Fig. 14. Subsectoral activity indicators: ratio to GDP.

exception of trucking, the trends in the other end uses' relation to GDP have enhanced the effect of declining intensities on lowering energy requirements per GDP. Of particular interest in recent years is the fact that for the first time, this structural relationship has played a more important role than declining intensities in lowering the E/GDP contributions from manufacturing and auto travel.

4.2. Sum of decomposition effects

Combining the decomposition results from all sectors provides an overview of how the indicators have affected total energy use in the economy and captures the effects of all uses, not just those depicted in the previous section. This is done by summing the sectoral decomposition results for each component, expressed in energy terms using 1990 as a base. Fig. 15 shows the results expressed both in energy units, on the right-hand axis, and as an index, on the left-hand axis. In addition to the energy services and intensity indicators, Fig. 15 includes a GDP index, which equals the real GDP scaled to its 1990 value.

Total delivered energy use rose 15%, from 51,900 to 59,500 PJ. The energy services index, which at the economy-wide level combines economic and physical measures of activity, had the effect of driving energy use up by 24%. The total intensity effect, on the other hand, declined by only 7% over this period. Interestingly, the intrasectoral structural aspect of energy services had almost no net effect on energy use. This does not mean that structural changes were not important. Only in the non-manufacturing industries and travel sectors did structural changes have relatively little effect. However, *increases* due to structural changes in the freight in residential sectors offset *decreases* in the manufacturing and service sectors.

We have shown that in individual sectors, energy use may decrease due to structural changes that do not indicate savings due to efficiency improvements in any sense. At the economy-wide level, another type of structural change may also affect energy use if GDP is considered a principal driver of energy consumption. After 1994 the energy services indicator in Fig. 15 does not rise as quickly as GDP. This is the principal component of the decline in E/GDP after that date. Examples of these changes for certain sectors include cases where pkm increase less quickly than GDP or as the manufacturing sector's share of GDP decreases (i.e. if manufacturing value added does not keep pace with overall economic growth). Further analysis of the E/GDP ratio is elaborated in the next section.

4.3. Decomposition of changes in energy per GDP

In our approach, the effects of the total demand for energy services per unit of GDP and of real intensity changes are depicted separately. The four sectoral decomposition charts provided in Section 3 (Figs. 4, 7, 10 and 12) reveal that in the 1990s intensities in the two

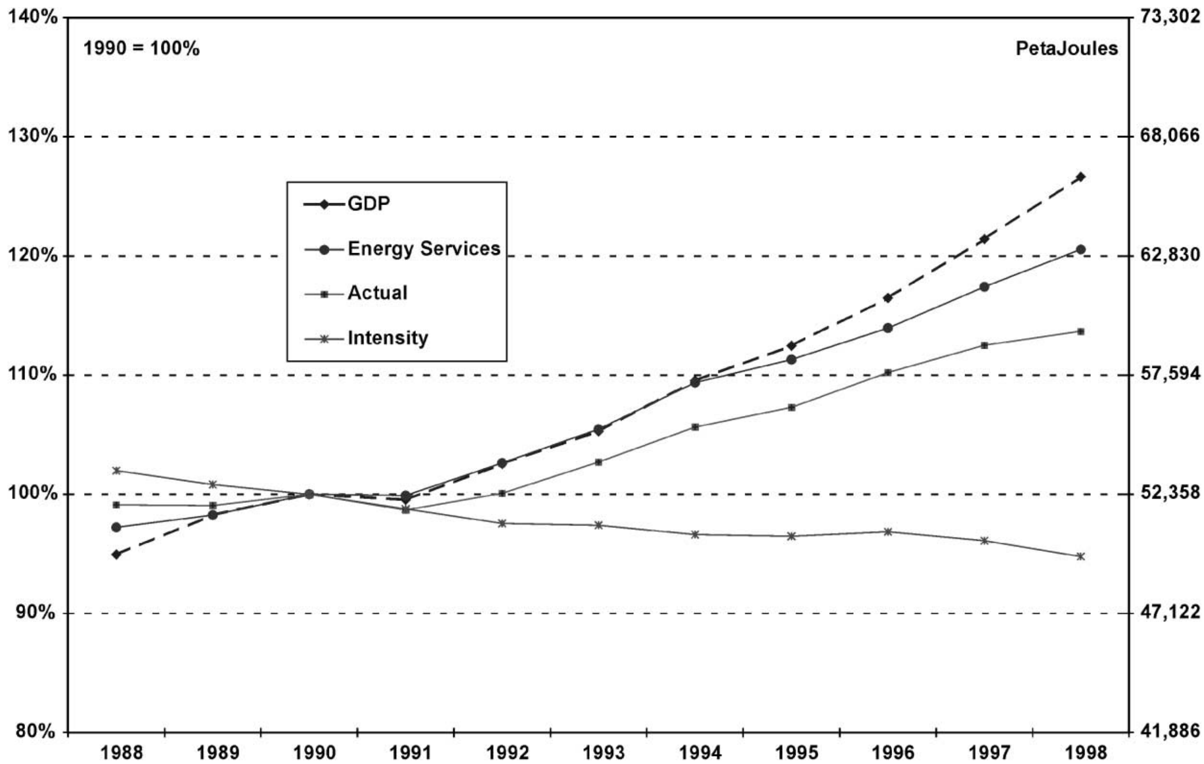

Fig. 15. Sum of energy use and decomposition effects across all sectors.

largest energy-using sectors, manufacturing and travel, began to level off. In both sectors intensity declined at rates well below those of the 1970s and 1980s. This is important because most of the energy savings in the previous two decades arose from these two sectors. Intensities in the residential, other industries, and freight sectors declined significantly in the 1990s, but to some extent increasing intensity in the service sector offset the energy savings from these sectors.

Fig. 16 shows the measures of growth in energy services to GDP, the structural side of the E/GDP coin. Note that this ratio fell markedly for every sector but freight. While this indicator remained steady or increased for most sectors during the late 1980s to early 1990s, since 1993 or 1994 it has declined rapidly, particularly for the large energy-using sectors, manufacturing, travel, and residential. In manufacturing this was due principally to the rise of light manufacturing, especially electronics. In the travel sector, where structural changes had little effect, the decline in energy services/GDP is due mostly to the fact that overall activity (pkm) did not rise as quickly as GDP. In the residential sector both structural and activity indicators put upward pressure on energy use, but factors such as floor area and appliance ownership did not increase as quickly as GDP.

When the changes in intensities and energy services/GDP are summed across all sectors, we obtain a decomposition of E/GDP for the entire economy. The trend in the index of the E/GDP ratio and its decomposition factors are shown in Fig. 17. The E/GDP ratio has fallen by 14% since 1988. Our analysis shows that the structural effects can be extremely important, as in the case of manufacturing after 1993, where they had an important impact on the ratio of energy use to GDP even though the combined effect of individual manufacturing intensities had little effect on the sector as a whole. Decreases in energy intensity explain most of the drop in the E/GDP ratio until 1994. Since then, the change in energy services per GDP has been predominant, as this ratio fell 5% between 1994 and 1998. This means that most of the decline in the E/GDP ratio in recent years is attributable to the fact that the booming economy of the late 1990s has surged ahead of the activity indicators of the individual sectors. This is a sharp contrast to previous time periods when intensity changes accounted for most of the recorded drops in E/GDP.

4.4. Growth rates in GDP, energy services and intensity indicators: 1988–94 vs. 1994–98

With the economic growth that occurred in the wake of the recession, the relationship of the economy to energy use changed considerably. While the ratio of E/GDP decreased only slightly faster in the latter part of the study period, in recent years the reason for the decline has reversed. Fig. 18 depicts how both intensities

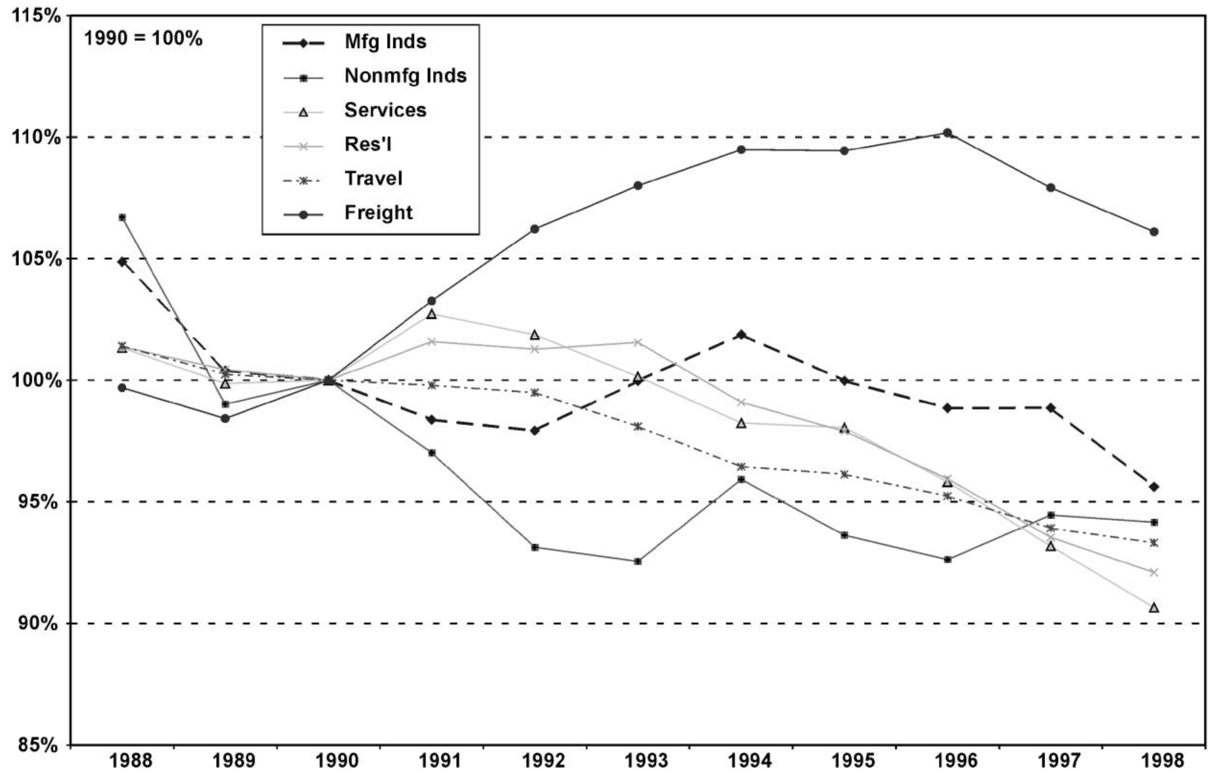

Fig. 16. Energy services (AWD Indices) changes per GDP by sector.

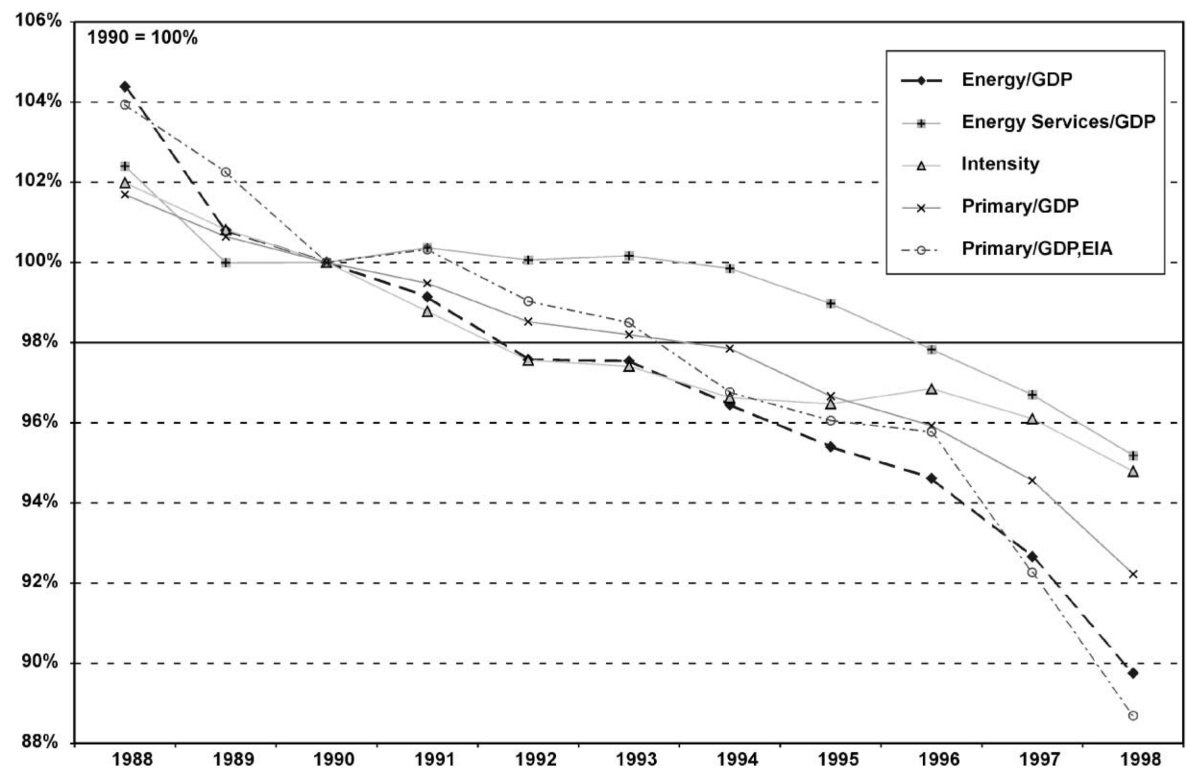

Fig. 17. Decomposition of changes in energy use and GDP.

and the ratio of energy services demanded per unit of GDP (ES/GDP) from each of the sectors have changed in the period from 1994 to 1998 compared to the preceding period. For each sector, the average annual rate of change is given for both indicators for each period. In most sectors, the path of these indicators

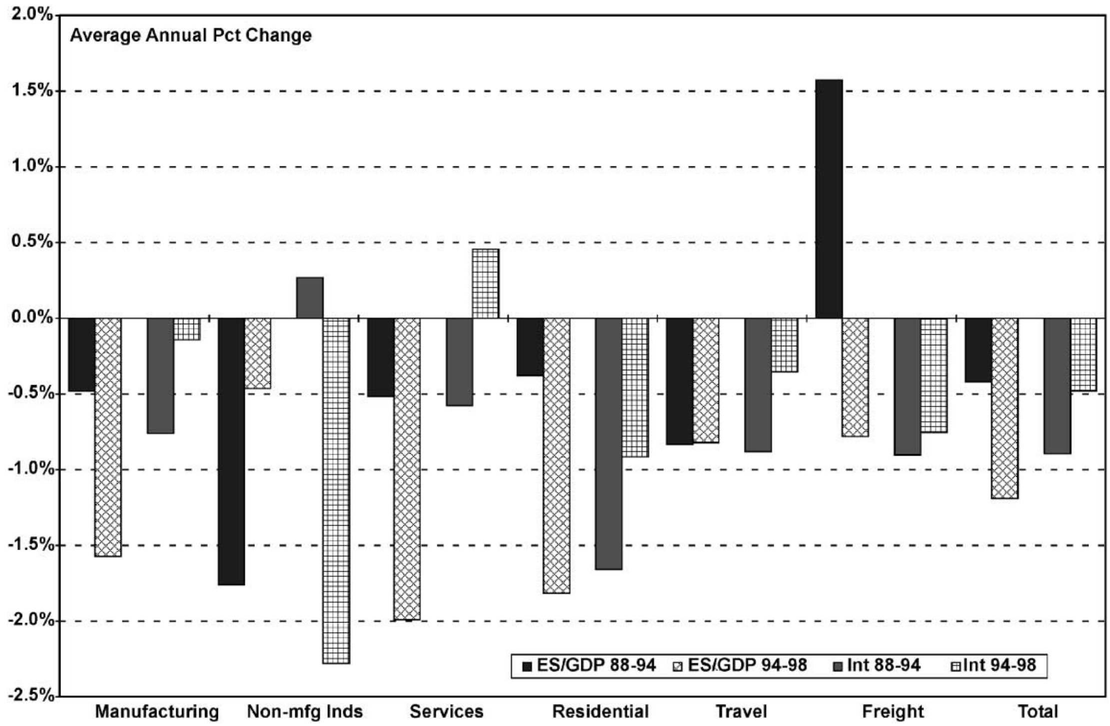

Fig. 18. Average annual growth rates in energy per GDP indicators, 1988–1994 vs. 1994–1998.

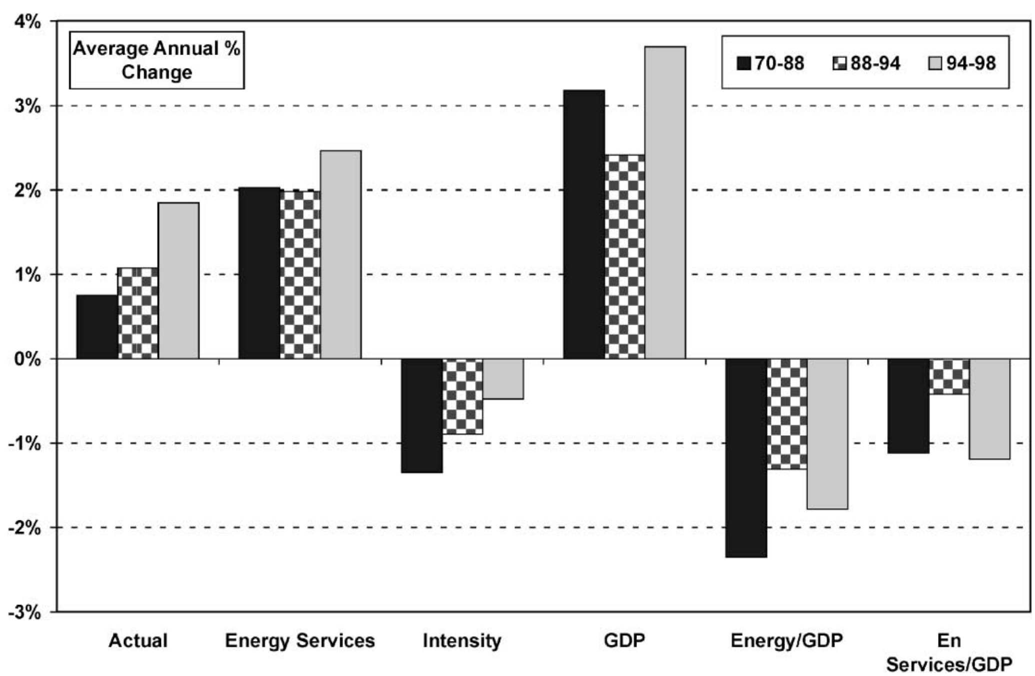

Fig. 19. Comparison of structural and intensity changes on energy use.

changed radically in the early to mid-1990s. Note that for all sectors but travel and other industries, the rate of change in energy services to GDP declined markedly, in the case of the services, freight and residential sectors, by 1.5% or more. In contrast, intensities did not decline as quickly in the latter period in all sectors but non-manufacturing industries.

The final stack of bars on the right side represents the effects of the ES/GDP ratio and intensities summed across the entire economy. The annual rate of change in the ES/GDP ratio fell from almost −0.5% to over −1%. At the same time, the average intensity change increased from about −1% to < −0.5%. This suggests that since 1994 less energy has been truly "saved" compared to the 1988 to 1994 period. Indeed, the fall in the ES/GDP ratio has been due mostly due the rapid growth of non-energy-intensive industries and services in the 1990s. Specifically, the industries and services exhibiting the highest rates of growth in the 1990s were "electronic and other electrical equipment", "non-depository institutions", "security and commodity traders", "telephone and telegraph", "business services", and "wholesale trade". Moreover, the economic growth arising from these industries did not engender matching increases in the physical drivers of energy consumption in the freight and residential sectors.

If we compare the present results with those from the earlier time period studied in Murtishaw and Schipper, 2001, even stronger contrasts are clear. Fig. 19 shows that from 1970 to 1988, energy intensities fell by over 1.3%/yr, much more rapidly than during recent years. Energy services per unit of GDP ratio fell by about 1.1%/yr in the first period, which combined with the intensity changes, led total E/GDP to fall by nearly 2.4%/yr. From 1988 until 1994, intensities declined more slowly and the structural indicator, energy services, fell slightly, although much less than GDP. Together these two trends reduced the decline in the E/GDP ratio to about 1.2%/yr. Since 1994 that ratio has begun to fall more quickly, despite a further slowing in the decline of energy intensities. This was enabled by the fact that rapid growth in GDP has outstripped demand for energy services. *While the ratio of energy to GDP declined throughout the late 1990s, the main reason was not improvements in energy efficiency but structural change*.

5. Conclusions: energy use in the "new" economy

Important changes have taken place in US energy use since the mid-1990s when the E/GDP ratio began to fall at rates not seen since the early 1980s. Whereas the main cause of the decline in the 1970s and 1980s was lower energy intensities, most of the decline since 1994 has been due to two kinds of structural changes in the economy:

- GDP growth in manufacturing was led by non-energy intensive industries. Between 1994 and 1998 this development reduced aggregate energy use in manufacturing, relative to manufacturing value added, by over 8%.
- Physical measures of activity in the economy, such as automobile or truck km driven, home area heated, services floor area per value added, or ownership of electric appliances have generally not grown as rapidly as GDP since the 1960s. However, this measure of energy services demanded per unit of GDP generated began to fall rapidly after a period of little change from the mid-1980s to the mid-1990s.

For the first time since data are available for analysis (1960), structural changes had a larger impact on the E/GDP ratio than did energy intensity changes. What led structural changes to overtake intensity as the predominant factor? One obvious response is that lower energy prices (at least until 1999) finally took their toll on manufacturing energy intensities and auto fuel intensity, resulting in slower energy savings in the US economy. At the same time, saturation of car use or even total travel may be appearing, i.e., further growth in GDP does not generate the same increment of car use or flying as it did in the past. Part of this phenomenon may be related to a lag between income growth and increased travel. However, the gap between GDP and vkm increased even further in 1999 (DOT, 2000). The same relationship may be true for purchases of some large household appliances and saturation of trucking for freight haulage.

To what extent are these developments related to the "information economy", sometimes referred to more narrowly as the "internet economy"? To be sure, information and electronics technologies played a strong role in the growth of US manufacturing, reducing demand for energy services per value added in the manufacturing sector. Additionally, as Romm et al. (1999) have pointed out, strong anecdotal evidence shows how the internet is leading to energy saving in many sectors. A more detailed study of factors of productivity would be necessary to address the total contribution of IT to reducing industrial or service-related energy use relative to value added. However, at the level of disaggregation we have studied we do not see increased rates of decline in subsectoral energy intensities.

In this paper, we cannot quantify the extent to which the decline in E/GDP is related to the information economy. The only sure part of the answer is that the spurt of manufacturing value added in the mid- to late 1990s was clearly driven by IT production. But whether what is produced is being distributed, sold, and consumed on less energy *because* of the information economy cannot be determined yet. For example, there is no evidence that the lag in automobile use with respect to GDP was *caused* by the internet. Thus, there is still no hard evidence showing how it affects the use of personal vehicles, freight patterns, or energy use in the service sector, at least not on a large enough scale to markedly affect our indicators.

On the other hand, it is also clear that computers, computer accessories, and the internet itself now consume a small but significant share of the nation's electricity. An authoritative estimate by Kawamoto et al. (2001) put the share of electricity for computers, peripherals, and the internet at around 2–3% of the total in the late 1990s. We concur, since a substantially larger share would imply an increase in electricity consumption that has not been seen.

5.1. Implications for energy and climate policies

These changes have implications for both energy and climate policies. The slowdown in energy savings per se is a disappointment to those who hoped energy savings would be an integral part of restraining carbon emissions. But the good news is that energy saving opportunities, wherever they are, remain. Yet this slowdown in the decline of energy intensities is no doubt partly a function of the relatively low energy prices that predominated during most of the 1990s. It appears that the higher energy prices after 1998 may reinvigorate the energy savings seen in the 1980s.

Some structural changes responsible for slowing energy consumption since 1994 are not likely to be reversed. With weaker GDP growth, it is not likely that vehicle use will spring ahead of GDP or that heavy industry will rebound at the expense of light industry. However, the slowdown in output from information industries will appear as a shift back to the slightly more energy-intensive manufacturing mix of the early 1990s. Whether the E/GDP ratio continues to fall as rapidly depends on the way the present economy responds to the current downturn. On balance, however, the structural "savings" from the 1990s may cause a small but permanent shift in the E/GDP ratio.

5.2. Further work

It is clear that this analysis cannot be carried out at the aggregate level. That is, the ratio of energy use to GDP alone cannot be "analyzed" to discover which components of that ratio have changed the most. That ratio itself conflates the impacts on overall energy use of energy efficiency changes and structural changes. The present work has pulled those two components apart and showed that they provide significantly different contributions to changes in energy use during different periods. Further work will extend this analysis to CO_2 emissions using the same decomposition techniques. Where possible the analysis will be extended to 1999. Unfortunately, the fundamental barrier to further understanding of trends in more recent years remains the paucity of official US data describing energy use:

- There is no real measurement of automobile usage or fuel economy: all present estimates come from a circular calculation of fuel (gasoline) sales and car use that relies on guessing how much gasoline is used by cars alone, how much by light trucks, and how far each kind of vehicle is driven. Major components of trucking energy use and intensity, particularly the amount of tkm hauled, are only partly known.
- Manufacturing energy is only surveyed every 4 years, with at least a 2-yr lag in reporting the results. The next year measured will be 2002, and results will not be available until the end of 2004. Household and service sector energy uses are also measured only once every 3 or 4 yr since all three surveys are undertaken on a rotating basis. Moreover, there is no reliable survey of energy uses in agriculture, mining, or construction. Hence energy use by end use or subsector across all the major stationary sectors can only be determined by approximations and interpolations.[8]

As a consequence of these basic deficiencies in US energy data, analysts must often speculate about the nature of aggregate changes in US energy use. Policymakers and analysts have to wait for years for some key data, which hinders both timely analysis and informed policy responses. Indeed, popular claims about improvements in energy efficiency based on the ratio of energy to GDP are clearly incorrect. Our understanding of how energy users respond to the policies that are enacted as well as other forces is obscured by such claims. Only a more continuous reporting of key data and analysis of those data permits accurate assessment of the nature of changes in the energy use—economy link and its implications for energy-related greenhouse gas emissions.

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